

BALLISTIC MULTI-ASTEROID FLYBY TRAJECTORIES OF LARGE MAIN BELT ASTEROIDS[#]

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In order to provide interesting multiple asteroid flyby trajectories in the main belt a technique has been developed which yields dates for a single trajectory that might encounter two large objects, one before aphelion and one after. The technique also allows determining single targets which can be encountered on a two year loop that goes out just beyond 2.1 AU. Each two year loop is then taken as the launch loop for two year Earth gravity assist trajectory that precedes and utilizes the larger loop involving two targets, Thus arc found trajectories which fly by three large asteroids with a launch that has the C3 of a two-year DVEGA, a modest post launch deltaV, and a flight time of four years or slightly less. About fifteen such trajectories have been found per year and those for 2003 and 2004 are given,

INTRODUCTION

At the present time asteroid flyby missions are still considered to be useful only if they can be easily accomplished on missions with other goals. The primary reasons for this are: (1) the fact that to reach the asteroid belt a substantial total impulse is required, (2) that almost no sets of large asteroids have been found available on single trajectories, and (3) that the asteroid mission proponents have said that only a rendezvous can accomplish the necessary goals of asteroid missions. The latter suggestion thus implies the use of low thrust solar or electric propulsion. But such a system is only now being tested for the first time. The goal of this paper is to return to ballistic trajectories and to describe a technique for finding ballistic multi-asteroid trajectories that would encounter three to five fairly large asteroids in three to five years of flight. It is hoped that a set of such trajectories would provide the means to begin to study a wide selection of large asteroid types in a few years. This paper is a preliminary report on the scheme described and at present sample trajectories for only two launch years, 2003, 2004, are available.

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THE ASTEROID POPULATION

The majority of asteroids orbit the Sun in what is known as the Main Belt which is generally taken to be between 2 AU and 4 AU (The Earth is at 1 AU). These are the targets with which this paper is involved except that only the : large ones are to be considered. A “large” asteroid is taken to be one of at least 20 km. radius. Since the radius of many asteroids has not been measured it is necessary to make an estimate of the radius for these cases. This is done by using ‘h’ and ‘g’ which are the absolute magnitude of the asteroid and an estimate of its reflectivity. The values obtained may not be very close to the actual radii but they serve to select the larger ones. With the 20 km. radius lower limit there are about 800 large asteroids and if the value is lowered to 10 km about 3000 asteroids would be included. There are 7541 numbered asteroids in the file used in this study but actually only the first 2000 were tested.

If two asteroids are to be encountered on a single pass through the asteroid belt it is really essential that the encounter points lie in the same plane. The natural selection of that plane is to use the ecliptic. Thus the encounters with the asteroids will be taken to be at the nodes of the targets in the search technique, and the trajectories eventually discovered to be near the ecliptic.

Another important consideration is the actual distribution of large asteroid nodes in the Solar system. There is only one large asteroid with perihelion under 1.7 AU and hence the possibility of anode under 1.7 AU. At 1.9 AU the number has already increased to **26**, Hence there are many nodes that will be included in our first list at 2.1748 AU (aphelion of a two year Earth to Earth trajectory), and more and more as the aphelion distance is increased

REACHING THE MAIN BELT

The ballistic trajectory requirements for reaching the main belt are indicated in Table 1, which gives the launch (and Earth flyby) requirements and the aphelion distances reached to obtain several Earth resonance trajectories. It is seen that the resonance 3/2 will not be of interest for large asteroids, and that all resonances lying between 2/1 and 3/1 would reach the inner part of the main belt, and that the data on 2/1 and 3/1 resonances covers the ranges of aphelion distances and Earth departure velocities needed for obtaining the trajectories sought for in this study.

It is the Earth gravity assist concept that allows traversal of the asteroid belt with smaller impulse requirements than for direct launches. They do cost a few months or weeks of time. A return to Earth is thus a part of every trajectory, and it is clear from Table I and the above described density of targets that the two year return offers the possibility of an asteroid encounter and a two year delta-V Earth gravity assist, a DVEGA. The impulse near the aphelion to increase the Earth flyby speed is roughly one sixth of the gain in flyby speed it produces. Thus it is concluded that the two year

resonance will be feasible for the launch and the flyby of one large asteroid, and that an Earth gravity assist at the end of the two year loop could be expected to reach as far as to 3.1 AU with a delta-V of about 350 m/s(= 1/6 (7.- 5.) km/s), Further Earth returns are not likely to be considered because of the long times needed for the return. Further flybys on the next loop back out to the main belt are possible if the spacecraft continues to function.

Table 1
DIRECT LAUNCHES FROM 1 AU INTO THE MAIN BELT

| Orbit Aphelion | Earth Resonance | Launch Energy (C3) | V-inf.@Launch |
|----------------|-----------------|--|-------------------|
| 1.62 AU | 3/2 | 11.1 km ² /sec ² | 3.34 km/sec |
| 2.17 AU | 2/1 | 25.8 km ² /sec ² | 5.08 km/sec |
| 2.68 AU | 5/2 | 38.1 km ² /sec ² | 6.17 km/sec |
| 3.16 AU | 3/1 | 48.0 km ² /sec ² | 6.92 km/se |

FINDING MULTIPLE TARGETS

The scheme for finding two large targets on a single loop into the main belt is similar to that used to find two Trojans flybys on a single loop out and back(Ref. 1). For the Trojans an aphelion distance set at some value just beyond the nodes of most of the Trojans. Here the same calculations are made for aphelion distances beginning with 2.1748 AU(to find an asteroid target for the first loop). For the remainder of the data set aphelion distances were chosen to be 2.3 AU, 2,4 AU etc to 2.8 AU. For each node of each large asteroid from 2003 to about 2025 the dates one would have to leave the Earth's orbit at the perihelion of the transfer are determined for both type 1 and 2 trajectories. The Earth's actual longitude is determined for each date and the line of data kept when the difference is less than 30 degrees. The final table for each aphelion distance is then sorted on Earth departure date. and printed so that one can spot cases when both a type 1 and a type 2 can be used to reach two targets on the same trajectory. The tables will be extended to include trajectory types 1, 2, 3, and 4 so that if a continuation to a second main belt loop is possible large targets may be found for it as well.

VENUS-EARTH GRAVITY ASSIST TRAJECTORIES

Using a flyby of Venus to cause the increase in speed at the Earth flyby is even more" effective in reaching the asteroid belt as was shown by Bender and Friedlander in 1975 (Ref. 2) They showed that all twenty of the first twenty asteroids were accessible on VEGA trajectories at one of two Venus inferior conjunctions. Two of the cases had C3 less than 10.0 km²/sec². The DV-EGA type of trajectory is always available since only the Earth and the target are involved, but for the VEGA type Venus is involved so

that the targets have to be found for the actual Earth flyby date that occur,. Thus the scheme outlined for DV-EGA's is also applicable for Venus-Earth gravity assists (VEGA's). Unfortunately VEGA'S often call for high values of the declination of the launch asymptote. Good cases do exist and will be included in later versions of this paper.

ASSEMBLING THE RESULTS

As it has been mentioned the data list obtained for 2,1748 AU was used to find two year Earth to Earth trajectories that would flyby by a large asteroid, There are an average eight lines per year for 2003 through 2009. Each of them is to be tested because only one asteroid encounter is expected and it can occur before or after the aphelion. The minimum C3 for two year orbits is about $26 \text{ km}^2/\text{sec}^2$ which corresponds to total delta-V (dvt) of 4.35 km/sec. About half to the cases tested so far have nearly the minimum C3 and little if any post launch delta-V. These asteroids become the first one to be encountered on our trajectories.

In order to find asteroids for the second loop after any one of the above selected targets the date of the Earth return is written down with 25 day limits both shorter and longer for the search, These off-sets correspond to the two types of DVEGA's the 2- and the 2+. Now each data list corresponding to one of the different aphelia that might be reached is searched for matches of dates. The possible targets are written down with asteroid number, trajectory type, and flight time from Earth. The search is for cases when the same trajectory might have both a type 1 and a type 2 encounter. Finally each pair that might conceivably be linked on a single trajectory is tested with the trajectory optimization program to identify the trajectories sought.

The trajectories that have been found for launches in 2003 and 2004 are listed in Table 2. The sequence of trajectories listed is first by numerical order of the first targets in the year. Under each of them the order is that of total **deltaV**. Values up to 5.5 km/sec are included. For each trajectory the first line contains the numbers, names, classifications (if known), and radii of the three targets. The data listed on the second line is only the launch date, the C3 in km^2/sec^2 , the post launch deltaV in km/sec, and the total flight time in years. Details of any trajectory can be supplied to any one interested. All of them include a two year loop with one target and a gravity assist flyby of Earth. The latter are so little demanding in the turn required that all occur at altitudes far above the surface of the Earth.

CONCLUSIONS

It has been shown that the technique of generating the tables of possible launch dates for both type 1 and type 2 trajectories to every accessible node of the 800 largest asteroids has made it possible to obtain numerous trajectories that encounter three of them in four years. Data for launches in 2003 and 2004 has yielded about 15 trajectories per year and the search tables generated do allow the study to be extended a few more years

into the future. The possibility of using the technique to find multiple targets for Venus Earth gravity assist trajectories has not yet been attempted but it is intended that it be done. The tables will be extended to include types 3 and 4 because they will place the spacecraft into the loop through the asteroid belt with a $C3$ less than $15 \text{ km}^2/\text{sec}^2$. For VEGA's there is no possibility for a second useful Earth return. The extended tables would also provide targets for a second loop into the asteroid belt on all of the trajectories given by the DVEGA trajectories in this paper.

REFERENCES

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2. Paper No. AAS 75-086, "Multi-Asteroid Flyby Trajectories Using Venus Earth Gravity Assists", D. F. Bender and A. L. Friedlander at the AAS/AIAA Astrodynamics Specialists Conference, Nassau, Bahamas, 28-30 July 1975.

Table 2
BALLISTIC MULTI-ASTEROID TRAJECTORIES 2003-2004

| Line 1: | Targets (N o. Name, CL,Rad) | Line 2: | (L. Date. C3,PLDV,TFT) | | |
|---------|--------------------------------|---------|-----------------------------|-----|------------------|
| 50 | Virginia X 50 3/8/03 29.7 | 432 | Pythia S 23 0.347 3.8 | 109 | Ferlicitas GC 45 |
| 50 | Virginia X 50 3/3/03 30.5 | 2 6 9 | Justitia 2 3 0.615 3.67 | 7 | Iris s 100 |
| 50 | Virginia X 50 3/22/03 43 | 37 | Fides S 73 0.137 3.82 | 7 | Iris s 100 |
| 796 | Sarita XD 22 3/13/03 25.6 | 432 | Pythia S 23 0.297 4.01 | 219 | Thusnelda S 20 |
| 796 | Santa XD 22 3/13/03 26 | 54 | Alexandra C 83 0.641 3.2 | 386 | Celutas S 82 |
| 796 | Sarita XD 22 3/26/03 29.6 | 37 | Fides S 54 0.501 3.87 | 7 | Iris s 100 |
| 796 | Sarita XD 22 3/13/03 25.9 | 103 | Hera S 46 0.675 3.81 | 139 | Althaea S 29 |
| 796 | Sarite XD 22 3/13/03 26.8 | 2 6 9 | Justitia 2 7 0.775 3.64 | 7 | Iris S 100 |
| 585 | Bilkis C 29 9/1 0.2003 26.2 | 1639 | Bower 20 0.826 3.69 | 99 | Dike C 36 |
| 585 | Bilkis C 29 9/1 1/03 26.3 | 524 | Fidelio XC 36 1.161 3.63 | 287 | Nephthys S 34 |
| 585 | Bilkis C 29 9/8/03 26.2 | 142 | Polana F 28 1.201 3.57 | 51 | Nemausa CU 74 |
| 27 | Euterpe S 66 8/5/04 27.3 | 7 | Iris S 100 0.313 3.58 | 41 | Daphne C 87 |
| 27 | Euterpe S 66 8/1 /04 25.6 | 8 8 2 | Swetlana 2 2 0.595 3.44 | 15 | Eunomia S 128 |
| 27 | Euterpe S 66 7131/04 27.3 | 7 | Iris S 100 0.629 3.5 | 275 | Sapientia X 58 |
| 140 | Siwa P 55 1 /24/04 25.6 | 198 | Ampella S 29 0.246 3.69 | 194 | Prokne C 84 |

Table 2 continued

| | | | | |
|-------------------------------|------|-----------------------------|------|-------------------|
| 140 Siwa P 55 1 /26/04 | 26.4 | 431 Nephele B 48 0.54 | 3.93 | 829 Academia S 48 |
| 140 Siwa P 55 1/28/04 | 25.2 | 1127 Mimi CX 23 0.884 | 4.07 | 1251 Hedera E 22 |
| 140 Siwa P 55 1/28/04 | 25.2 | 198 Ampella S 29 0.69 | 3.71 | 1251 Hedera E 22 |
| 140 Siwa P 55 1 /26/04 | 25.3 | 336 Lacadiera D 35 0.763 | 4.13 | 182 Elsa S 22 |
| 140 Siwa P 55 1/28/04 | 25.4 | 198 Ampella S 29 0.783 | 3.51 | 829 Academia S 48 |
| 306 Unitas S 23 3/1 0/04 | 25.4 | 5 0 0 Selinur 2 2 1.057 | 3.99 | 192 Nausikaa S 52 |
| 335 Roberta FP 44 2/1 9/04 | 40.8 | 431 Nephele S 48 0.106 | 3.03 | 236 Honoria S 43 |
| 335 Roberta FP 44 2/7/04 | 25.4 | 198 Ampella S 29 0.862 | 3.73 | 236 Honoria S 43 |
| 335 Roberta F? 44 2/6/04 | 25.4 | 198 Ampella S 29 0.862 | 3.73 | 236 Honoria S 43 |
| 505 Cava FC 58 7/1 5/04 | 28.7 | 7 Iris S 100 0.242 | 3.71 | 77 Frigga MU 35 |
| 505 Cava FC 58 7/1 6/04 | 28.5 | 7 Iris s 100 0.377 | 3.94 | 7 9 9 Gudula 2 2 |
| 505 Cava FC 58 7/1 6/04 | 28.4 | 7 Iris s 100 0.57 | 4.21 | 585 Bilkis C 29 |